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Dust and environment in the Southern High Plains of North America

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Continuous measurements of dust reveal the intermittent nature of dust events within the Southern High Plains of North America. Dust events appear as sudden peaks that project outward from a much lower background dust concentration. The measured dust record appears to follow a regular annual cycle with most dust events occurring in spring and considerably fewer during other seasons. The annual dust cycle reflects seasonal changes in environmental factors such as wind speed, surface cover, and moisture conditions. Most dust events are associated with a combination of strong winds, negligible surface cover, and dry conditions, all of which occur most frequently during the spring season. Wind speed alone is found to be an imperfect indicator of dust levels in the Southern High Plains because of the moderating effects of other important environmental factors such as humidity and surface cover. However, if one limits consideration to dry and bare conditions, dust concentration exhibits a positive correlation with daily wind speeds above 4 m s^{-1} and a negligible correlation for light winds.

Keywords: dust; particulate matter; PM_{10}; wind erosion; environment

Introduction

The following report is based on an 18-month investigation of ambient dust in the Southern High Plains of North America conducted by the USDA-Agricultural Research Service in 1996 and 1997 (Stout *et al.*, 1999). During this study, an attempt was made to obtain a continuous record of daily dust samples and a record of basic meteorological data using a combined dust sampling system and meteorological tower located in north Lubbock, Texas. In addition, information regarding land-surface conditions was gathered weekly from the Texas Agricultural Extension Service. This paper summarizes the measured data and examines the influence of environmental factors, such as surface cover and climate, on measured ambient dust levels.

Physical setting

The Southern High Plains (SHP), shown in Fig. 1, is an immense plateau located in north-western Texas and eastern New Mexico. The uppermost soils of the SHP were formed by the slow and gradual process of aeolian deposition on grassland vegetation

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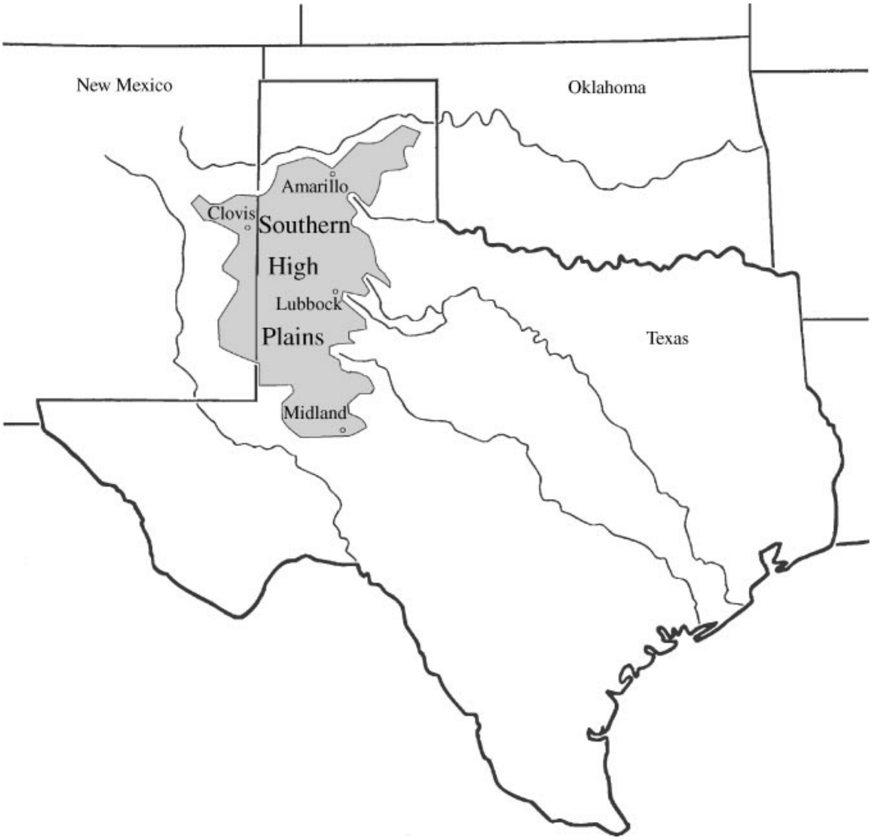

Figure 1. The Southern High Plains of North America.

(Gustavson & Holliday, 1999). Within the last century, however, most of the natural grassland vegetation has been converted to a vast patchwork of highly erodible cropland. In the modern SHP, one is more likely to see intermittent periods of intense wind erosion rather than the gradual aeolian deposition of the past. When conditions are right, wind eroding fields emit individual dust plumes that combine with plumes from other fields to form regional-scale dust plumes that spread across the vast expanse of the SHP and beyond. In a sense, the entire plateau becomes a large area source that produces dust plumes on a scale comparable to that of its source region.

Past work

Past research in arid and semi-arid agricultural environments has shown that elevated particulate matter levels are often associated with regional-scale wind erosion events (Chepil, 1957; Laprade, 1957; Nickling & Gillies, 1993; Marticorena & Bergametti, 1995; Saxton, 1995). Strong winds blowing across a patchwork of cultivated fields may produce elevated dust levels associated with regional dust storms (Sazhin, 1988; Lee *et al.*, 1994).

Atmospheric conditions and land-surface conditions constitute the environmental conditions which control the frequency and intensity of dust storms (Middleton, 1984; Jauregui, 1989). Specific environmental conditions may depend somewhat on location but clearly there are common factors. For example, negligible surface cover, low surface soil moisture, strong winds, and low humidity are important environmental factors that are often associated with dust events (Warn & Cox, 1951; Jackson *et al.*, 1973; Jauregui, 1989). In most cases, the exact influence of each factor on regional dust levels is still imperfectly understood and less is understood about the combined effects of multiple environmental factors.

Dust emissions from semi-arid regions vary in time as environmental conditions change with the seasons (Warn & Cox, 1951; Brown *et al.*, 1968; Smith *et al.*, 1970; Jackson *et al.*, 1973; Orgill & Sehmel, 1976; Goudie, 1983; Brazel & Nickling, 1986; Wigner & Peterson, 1987; Lee *et al.*, 1994). Past attempts to define seasonal and long-term variations in dust storm frequency have relied heavily on visibility observations as a surrogate for direct dust concentration measurements, (Pecille, 1973; Orgill & Sehmel, 1976; Pollard, 1977; Changery, 1983; Goudie, 1983; Wigner & Peterson, 1987; Lee *et al.*, 1994; Lee & Tchakerian, 1995). Before 1993, visibility was routinely estimated each hour by a National Weather Service observer who attempted to see fixed objects at known distances from the station. When visibility decreased to less than 7 miles, a note was made as to the reason for the reduced visibility. In semi-arid agricultural regions, the occurrence of blowing dust was sometimes reported as the reason for reduced visibility and, as a result, National Weather Service surface observations provide a valuable record of blowing dust that often extends as far back as 1947.

Unfortunately, visibility is a subjective measurement that depends upon the judgement of the observer and the observer's ability to detect distant objects (Orgill & Sehmel, 1976). Thus, two observers may describe the same conditions differently and it follows that observations taken at two different locations by two different observers may not be directly comparable. Certainly direct measurements of dust concentration would be preferable.

Direct measurements of particulate concentration have been obtained at various times in many major cities in the United States by state and federal regulatory agencies concerned with air pollution. The purpose of these monitoring programs has been to establish whether a city or region was in compliance with current air quality standards. As air quality standards for particulate matter have changed through the years, so has the focus of these programs.

In the Lubbock area, samples of total suspended particulates (TSP) were obtained from 1961 to 1982 at sampling frequencies that varied from once every 2 weeks to once a week (Cowgill, 1970). Sampling was suspended from 1983 to 1986 until a program focused on particulate matter with a mass median aerodynamic diameter less than 10 μm (PM_{10}) was initiated in 1987. In the case of PM_{10}, sampling frequencies varied from once every 2 days to once a week.

Data collected during these regulatory monitoring programs remains an untapped reservoir of potentially valuable information regarding wind erosion activity within semi-arid agricultural regions such as the SHP. The present study adds to and improves upon the existing dust record in a few significant ways. First, this study was a scientific study focused on wind erosion rather than a regulatory monitoring program focused on compliance with air pollution standards. Second, unlike past monitoring programs where many days were skipped between samples, here an attempt was made to obtain a more continuous record of daily dust samples to reduce the possibility of missing major dust events. Third, an attempt was made to look in more detail at the influence of environmental factors such as regional surface cover and climatic factors on measured ambient dust levels.

Experiment

From 23 March 1996 to 30 September 1997, an attempt was made to obtain a continuous record of daily dust samples (PM_{10}) at a site located within the cotton-growing region of the SHP of North America. To obtain a regionally representative measure of PM_{10}, careful attention was paid to the placement of the sampling system. Locations

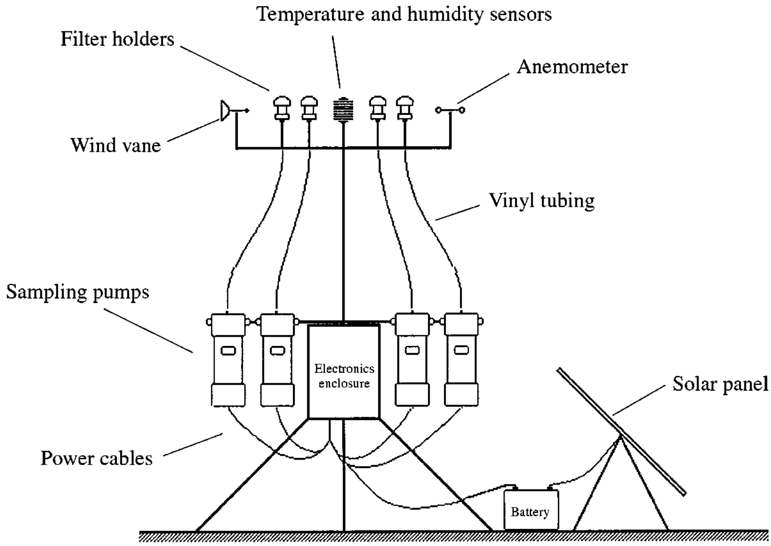

Figure 2. Schematic drawing of the continuous dust sampling system.

where a single eroding field might dominate the measurements were avoided since such local dust conditions may not represent true regional conditions. Congested sites were avoided so that industrial sources or heavy automotive traffic would not contribute significantly to the measurements. A grassland site was chosen since the site itself would not be a significant dust source and the site would not change significantly through time as surface conditions in the surrounding agricultural region varied seasonally. Such a site can provide PM_{10} measurements that reflect true regional dust conditions as they change with time.

A satisfactory site was found in north Lubbock, Texas at Lubbock Lake Landmark State Historical Park. Contrary to its name, the landscape of Lubbock Lake is predominantly grassland with a total area of $1{\cdot}5\ km^2$. This permanent grass cover contrasts sharply with the surrounding agricultural land which can quickly change from fully vegetated to completely bare in a matter of days. The non-eroding grassland provides a buffer zone between the surrounding agricultural fields and the sampling location. For winds blowing out of the east, south and west the nearest agricultural field is more than 1 km away. The grass buffer zone to the north is only 200 m due to a hay field that is located just north of the park boundary.

Continuous dust sampling system

A 2-m-tall tower was outfitted with four dust samplers as well as meteorological instrumentation, as shown schematically in Fig. 2. The key components of the tower include a data logger, a data storage module, a 12-V battery charged by a solar panel, four PM_{10} samplers, and an array of meteorological instruments that will be described later.

PM_{10} was measured with Airmetrics Minivol samplers*. While the Minivol is not a federal reference method sampler, a recent intercomparison study revealed that it

*Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may also be suitable.

provides results that closely approximate the federal reference method (Dutcher *et al.*, 1999).

Each sampler was connected via vinyl tubing to a separate filter holder assembly which consisted of a rain-protected inlet, a greased impaction plate and a 47-mm-diameter filter holder. Dried and pre-weighed polycarbonate filters (0·6-μm pore size) were installed in each of the four filter holders.

Continuous sampling was accomplished by running a single sampler each day from midnight to midnight local time. The active sampling pump pulled $5\,l\,min^{-1}$ of air across its assigned filter. After 24 h, the active sampler was switched off, and the next sampler in line was activated so that it pulled air through the next filter assembly for 24 h. This process was repeated as the system cycled through all four samplers in a continuous loop. Every few days, exposed filters were replaced by fresh filters. Exposed filters were then dried and weighed to determine the daily mass collected. PM_{10} concentration was calculated by dividing the sample mass by the total volume of air that passed through the filter in 24 h (7·2 m^3) and the result was reported in units of $\mu g\ m^{-3}$ of air.

Meteorological variables measured at the same site include wind speed, wind direction, air temperature, and relative humidity. All variables were measured at a common height of 2 m. Variables were sampled each second and averaged over one hour before output to final storage. Later, hourly values were averaged over 24 h to match the daily dust sampling period.

Results and discussion

The sampling tower was completed and dust sampling began on 23 March 1996. Data collected from 23 March 1996 to 30 September 1997 appear in Table 1.

The annual dust cycle in the Southern High Plains

Daily PM_{10} values measured at the Lubbock Lake site are plotted as a time-series in Fig. 3. Although the measured dust record is not long enough to conclusively define normal annual dust trends, the dust record does appear to follow a pattern established by past visibility studies (Orgill & Sehmel, 1976; Pollard, 1977; Goudie, 1983; Peterson & Gregory, 1993). Within the SHP, most observers agree that the majority of dust events occur during the spring season due to a combination of strong winds and a preponderance of dry and bare soils (Sidwell, 1938; LaPrade, 1954; Lee *et al.*, 1994).

The arithmetic mean concentration from 23 March 1996 to 23 March 1997 was 19·8 $\mu g\,m^{-3}$, a value well below the 50 $\mu g\,m^{-3}$ annual air quality standard established by the United States Environmental Protection Agency (Federal Register, 1987). The relatively low annual PM_{10} concentration is a result of long periods of relatively dust-free conditions punctuated by intermittent dust events.

Dust episodes appear as peaks that dramatically thrust outward from a much lower background concentration. The two highest PM_{10} values were recorded during Spring 1996 with values of 166·0 $\mu g\,m^{-3}$ on 13 April 1996 and 116·8 $\mu g\,m^{-3}$ on 24 March 1996. The third highest value was recorded during Spring 1997 with a value of 92·8 μm^{-3} on 27 March 1997.

The frequency of occurrence of dust events with a daily PM_{10} concentration twice the annual concentration (in this case, greater than 40 μm^{-3}) was calculated and the results are shown in Table 2. Note that the frequency for any season is generally very low indicating the intermittent nature of dust events. Frequency values for the spring season were clearly much higher than any other seasonal period with frequencies of 11 and eight

Table 1. *Daily PM_{10} measurements obtained at the Lubbock Lake site from 23 March 1996 to 30 September 1997*

	PM_{10} measurements ($\mu g\,m^{-3}$) at Lubbock Lake																		
	1996										1997								
Day	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1		15·4	22·9	15·7	19·3	32·5	19·2	15·0	11·0	7·1	21·3	38·3	9·7	17·5	69·3	12·4	13·1	29·4	16·0
2		40·4	23·9	11·9	22·4	32·5	16·9	21·7	9·0	10·1	16·5	22·1	8·3	13·9	42·6	19·3	18·3	29·9	24·3
3		28·6	29·4	—	14·7	29·9	17·5	16·8	24·2	13·3	81·8	32·1	9·3	3·1	20·4	21·9	29·0	31·8	24·4
4		12·5	27·1	—	22·2	19·6	8·9	16·9	15·7	11·4	19·6	16·7	10·4	14·6	29·4	19·7	11·9	19·3	19·4
5		—	32·6	40·7	28·2	21·5	12·2	18·6	18·3	14·6	19·0	9·9	12·5	36·5	45·7	16·5	17·4	24·4	—
6		11·8	30·7	38·1	23·3	35·1	17·9	14·0	13·2	19·7	7·8	6·4	10·1	11·8	43·1	10·0	8·2	23·6	20·6
7		8·8	32·5	21·7	18·1	21·0	16·4	16·9	19·7	—	4·4	9·4	15·0	18·2	29·0	22·5	18·5	2·8	20·8
8		—	23·6	16·7	21·3	7·9	6·9	14·0	20·4	21·5	6·1	14·7	11·9	—	24·6	8·8	21·8	4·0	33·1
9		13·5	33·9	17·8	16·4	10·6	13·1	18·5	26·8	23·5	4·7	13·5	13·9	1·7	13·2	6·8	21·5	10·7	23·2
10		19·9	21·9	20·4	13·2	10·8	9·6	15·6	27·1	23·3	6·7	17·4	13·9	11·4	16·8	7·2	14·9	18·3	—
11		13·9	12·9	28·6	18·1	16·3	17·8	20·0	26·0	64·0	—	18·3	16·5	7·1	4·9	13·1	12·2	21·1	11·5
12		26·0	19·4	14·2	18·0	12·5	14·0	16·9	23·2	20·1	—	18·8	12·6	8·2	13·6	9·7	18·2	16·0	18·8
13		166·0	20·7	17·6	21·3	18·2	14·2	16·7	16·7	18·6	—	10·4	16·5	15·7	15·6	17·5	15·6	17·9	17·9
14		60·3	35·0	16·1	14·0	19·4	—	15·1	13·9	19·0	7·4	9·9	9·7	11·4	20·1	14·0	14·0	11·5	9·3
15		19·0	12·8	15·3	16·0	21·8	8·5	17·6	20·0	15·4	7·5	12·5	12·2	22·8	18·8	6·8	13·8	8·6	13·2
16		27·4	31·4	16·4	22·8	19·7	8·9	14·9	18·1	16·5	9·4	13·1	12·8	22·4	23·3	7·6	20·3	8·9	11·8
17		30·4	35·1	18·9	24·4	26·3	2·9	10·6	7·8	19·2	11·0	17·1	18·5	21·0	20·6	9·7	24·9	18·3	13·5
18		26·0	32·1	21·1	19·3	27·1	13·5	17·9	14·9	20·8	13·5	20·8	52·1	14·3	20·7	12·2	32·6	16·7	13·9
19		56·5	24·9	22·8	27·4	22·5	10·4	19·6	—	23·9	11·9	16·7	21·1	14·6	17·9	36·8	17·1	—	11·0
20		25·3	67·5	19·2	18·9	19·6	11·4	19·9	24·9	23·2	13·1	10·3	26·8	19·3	16·7	20·3	22·1	11·4	18·1
21		25·6	26·3	18·1	18·1	13·8	12·5	9·7	13·3	17·9	12·4	8·5	23·3	24·0	14·9	14·0	21·8	—	11·7
22		18·8	11·8	19·0	58·6	22·5	15·8	7·2	10·4	14·7	16·5	11·0	13·2	4·9	16·9	9·2	17·6	—	9·2
23	82·5	29·7	22·2	22·2	22·2	10·1	18·9	10·1	31·9	14·2	39·0	8·8	18·9	12·9	15·8	41·7	20·6	—	16·7
24	116·8	35·4	44·7	21·3	12·5	7·5	18·2	19·9	26·9	14·4	13·3	11·4	64·0	9·0	24·2	26·7	26·9	12·6	8·2
25	16.9	33·3	15·7	16·1	11·5	6·7	17·1	22·8	18·9	13·1	19·2	5·3	26·4	3·3	21·0	14·0	29·0	—	13·2
26	14·4	37·8	—	12·8	17·5	9·6	10·8	49·9	11·7	21·7	12·5	7·4	19·2	4·9	21·3	4·0	24·2	23·9	9·2
27	—	22·4	—	13·3	11·8	11·9	6·0	14·4	17·5	18·6	24·9	8·6	92·8	9·3	15·7	12·9	16·3	27·4	22·5
28	21·3	79·3	15·1	17·1	23·8	7·6	9·7	10·1	10·7	18·2	14·9	18·1	45·1	13·6	12·5	16·8	18·8	21·9	22·4
29	61·3	15·7	16·8	26·4	23·8	5·3	10·4	11·3	7·2	14·0	12·6		55·6	24·3	14·9	17·4	20·0	22·7	19·9
30	—	24·4	17·5	16·4	18·8	14·0	10·7	16·4	4·7	21·0	14·7		17·9	12·6	14·0	13·5	21·0	20·0	26·8
31	10·6		—		21·7	22·1		11·7		25·8	32·1		16·5		12·8		14·9	18·4	

Each value represents a daily PM_{10} concentration ($\mu g\,m^{-3}$) arranged by month and day. Missing values, marked by a dash, are mainly due to system failures such as a low battery or sampling pump malfunctions that caused the system to shut down before a full 24-h sample was completed.

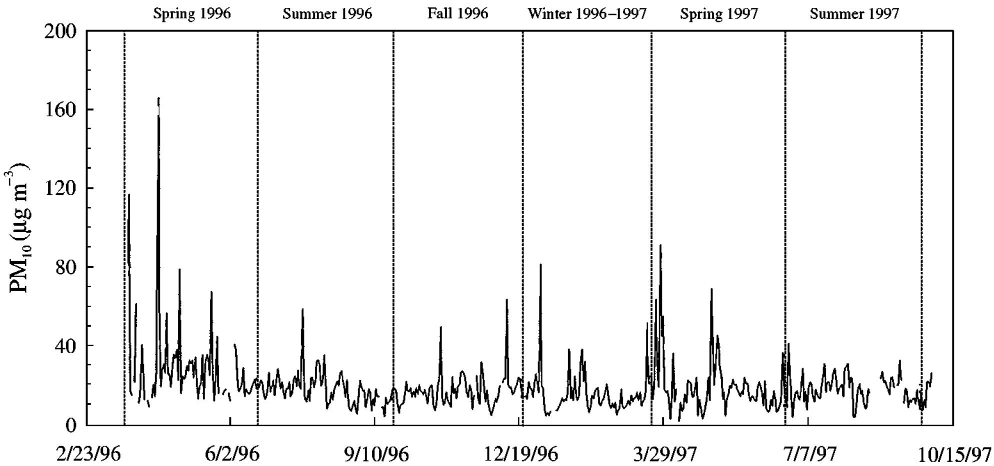

Figure 3. Daily PM_{10} measured at the Lubbock Lake sampling site in north Lubbock, Texas from 23 March 1996 to 30 September 1997.

dust events per season during spring 1996 and 1997, respectively. Values were around one or two dust events per season for any other season.

The seasonal mean PM_{10} concentration, $\bar{c}$, was calculated and the results are compiled in Table 2. The largest seasonal mean values were recorded during Spring 1996 and Spring 1997. The seasonal mean concentration was lowest during Winter 1996–1997.

The standard deviation of the daily PM_{10} concentration σ_c provides a measure of the day-to-day variability of dust levels and the ratio $\sigma_c/\bar{c}$, called the coefficient of variation, provides a relative measure of the dispersion about the mean. Values of σ_c and $\sigma_c/\bar{c}$ calculated for each season are included in Table 2. Both σ_c and $\sigma_c/\bar{c}$ were generally highest during spring and winter and lowest during summer and fall. High values of σ_c and $\sigma_c/\bar{c}$ during spring and winter reveal the highly variable nature of spring and winter dust storm seasons where intermittent dust events are more frequent.

In summary, the measured dust record appears to follow an annual cycle with the following characteristics:

(1) Dust events occur most frequently during spring and least frequently during summer;
(2) The seasonal mean concentration is highest during spring;
(3) Maximum PM_{10} values are considerably higher during spring than any other season; and
(4) Day-to-day variability is highest during spring and winter.

Environmental factors

The annual dust cycle reflects seasonal variations in environmental conditions (Smith *et al.*, 1970; Brazel & Nickling, 1987; Wigner & Peterson, 1987; Jauregui, 1989). The regional dust system may be conceptualized as a simple dynamic system where strong winds act upon the regional surface which then emits dust thereby increasing the regional dust concentration. For a given wind condition, regional dust emissions are modulated by environmental factors such as soil moisture and surface cover. Regional soil moisture conditions are not routinely reported by the National Weather Service nor

Table 2. *1996–1997 seasonal statistics for PM_{10} measurements at Lubbock Lake*

Season	Number of observations	Maximum daily PM_{10} concentration $\mu g\,m^{-3}$	Dust event frequency ($PM_{10} > 40\,\mu g\,m^{-3}$) events/seasons	Seasonal mean PM_{10} $\bar{c}$ $\mu g\,m^{-3}$	Seasonal standard deviation σ_c $\mu g\,m^{-3}$	Coefficient of variation $\sigma_c/\bar{c}$
Spring 1996	80	166·0	11	29·3	23·5	0·80
Summer 1996	93	58·6	1	17·7	7·7	0·43
Fall 1996	88	64·0	2	17·4	8·2	0·47
Winter 1996–1997	86	81·8	2	15·8	10·5	0·67
Spring 1997	91	92·8	8	19·6	14·4	0·73
Summer 1997	87	41·7	1	18·3	6·9	0·38

by any other agency. However, there are other meteorological variables, such as relative humidity and precipitation, that may be used as indicators of soil moisture if interpreted properly.

Wind and dust

Perhaps the most important environmental factor that influences dust concentration is wind. Although other factors may moderate dust emissions, wind provides the energy that drives the wind erosion process. Here we focus on daily-mean wind speed since dust samples were obtained over a 24-h period. As shown by Durst (1960) and Stout (1998), long-period mean winds are generally much lower than the intermittent short-period gusts which actually produce the blowing dust.

Daily wind speed, measured at a height of 2 m, is plotted as a time series in Fig. 4. Note that wind speed exhibits seasonal variations similar to the observed dust cycle with strongest winds occurring during spring and weakest winds during summer.

As summarized in Table 3, the seasonal-average wind speed was considerably higher during spring than any other season and spring had the highest fraction of days with daily wind speed, u, above 5 m s^{-1} whereas summer typically had the lowest seasonal-average wind speed and the lowest frequency of windy days.

Daily PM_{10} concentration is plotted as a direct function of the daily 2-m wind speed in Fig. 5. Note that all PM_{10} values greater than 80 μg m^{-3} occurred when daily wind speed was greater than 6 m s^{-1}. When wind speed fell below 4 or 5 m s^{-1} PM_{10} values generally clustered near the annual average of around 20 μg m^{-3}. There is considerably more variability of PM_{10} values for higher wind speeds. For example, PM_{10} values as low as 11 μg m^{-3} and as high as 166 μg m^{-3} were both associated with daily wind speeds between 6 and 7 m s^{-1}. Such a wide range of possible PM_{10} values for the same wind conditions reveals the influence of environmental factors other than wind, such as surface soil moisture and surface cover.

The large amount of scatter evident in Fig. 5 is also partly due to the 24-h averaging period. Most filter-based dust samplers, including the samplers used during this experiment, are designed to obtain samples over a 24-h period due to the fact that air quality regulations are based upon a daily-average concentration. However, dust events sometimes last only a few hours. A short but intense dust event may not be strongly correlated

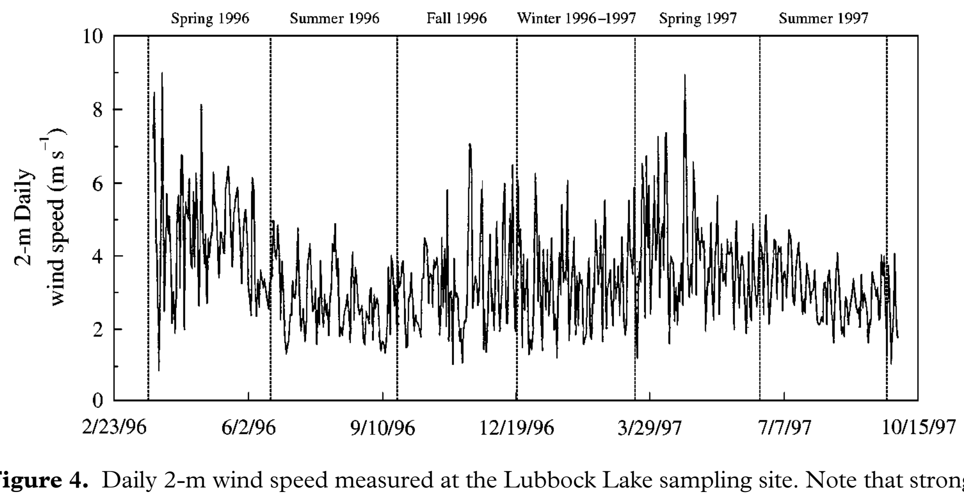

Figure 4. Daily 2-m wind speed measured at the Lubbock Lake sampling site. Note that strong winds occur most frequently during spring and less frequently during summer.

Table 3. *Seasonal wind statistics for Lubbock Lake*

Season	Seasonal average $\bar{u}$ m s^{-1}	Seasonal frequency of windy days ($u > 5$ m s^{-1}) number/season
Spring 1996	4·44	32
Summer 1996	2·76	0
Fall 1996	3·16	9
Winter 1996–1997	3·22	8
Spring 1997	3·90	15
Summer 1997	3·02	1

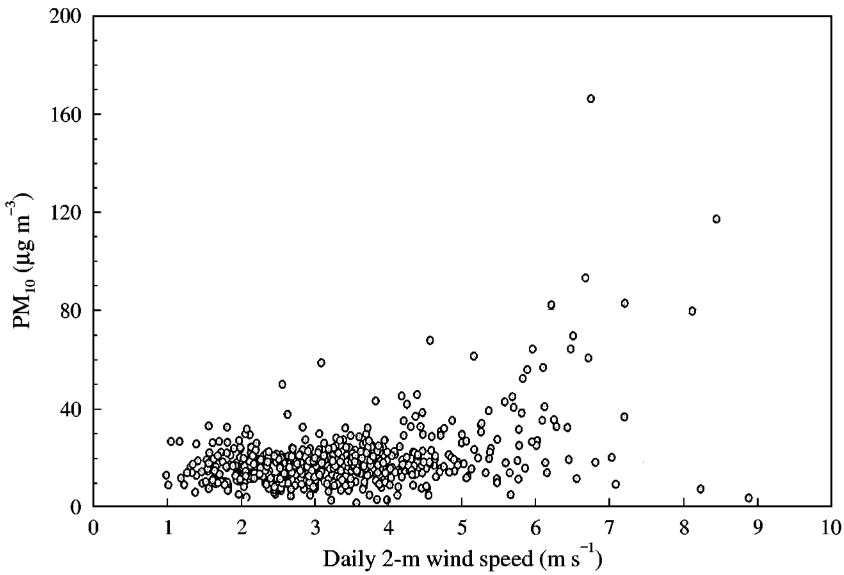

Figure 5. PM_{10} plotted as a function of the daily 2-m wind speed.

with a 24-h average wind speed. One would expect a clearer picture of the relationship between wind speed and dust concentration if hourly or shorter period sampling were used.

Surface soil moisture and dust

With regard to wind erosion, it is the soil moisture content of the few millimeters at the soil-air interface that is critical. If this thin surface layer is sufficiently moist then individual grains tend to adhere to each other and thereby increase the resistance of the surface to wind erosion (Saleh & Fryrear, 1995; McKenna-Neuman & Scott, 1998). During periods of high insolation and low relative humidity, this thin surface layer can dry quickly even when there is plentiful subsurface soil moisture.

Monitoring the moisture content of this thin surface layer across a region as large as the Southern High Plains is not easily accomplished nor is this type of information

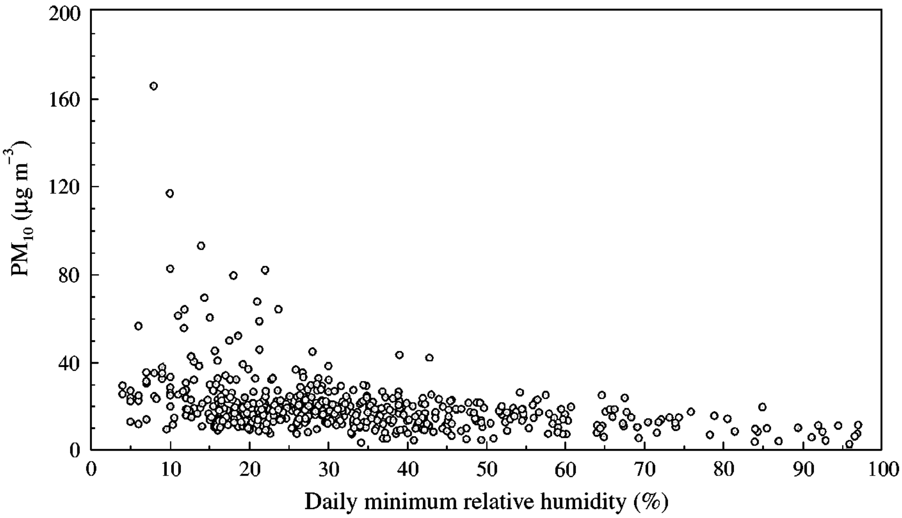

Figure 6. PM_{10} plotted as a function of the daily minimum relative humidity. Note that most dust events occur when the daily minimum relative humidity falls below 30%.

readily available. There is, however, at least one practical alternative to the use of surface soil moisture.

The moisture content of the upper soil surface is intimately linked to the moisture content of the atmosphere directly above it (J.M. Gregory, pers. comm.) Dry winds extract moisture from the surface more quickly than subsurface moisture can replenish it, leaving the uppermost soil surface desiccated and susceptible to wind erosion. On the other hand, moist air can produce a moistening of the surface layer as well as a reduction in evaporation. Thus, it is reasonable to assume that relative humidity may be used as an indicator of surface soil moisture at the soil-air interface.

During a typical day, relative humidity follows a daily cycle driven by diurnal temperature variations. Relatively moist conditions occur in the early morning whereas the minimum relative humidity often occurs around mid-afternoon. It is during this dry period, when relative humidity is at a minimum , that the potential for blowing dust is maximum.

A plot of measured daily PM_{10} concentration as a function of the daily minimum relative humidity is shown in Fig. 6. Note that most dust events were associated with a daily minimum relative humidity below 30%. In fact, all PM_{10} values above 80 $\mu g\,m^{-3}$ occurred when the minimum relative humidity fell below 30% and of the 25 values above 40 $\mu g\,m^{-3}$, 23 occurred when the minimum relative humidity fell below 30%.

It is also clear from Fig. 6 that it is possible to have low relative humidity without a large PM_{10} concentration. In other words, low relative humidity appears to be a necessary condition for a high PM_{10} concentration, but not a sufficient condition. There are other important factors, including wind speed, that influence PM_{10} but are independent of relative humidity. Thus, unlike wind speed, relative humidity should be viewed as a factor that can influence or temper dust emissions rather than as a driving force.

Rainfall is another commonly measured meteorological variable that can provide an indication of moist regional surface conditions if interpreted properly. However, as has been pointed out by Goudie (1983), the relationship between dust and rainfall is not a simple one. For example, rainfall at a sampling site may not be a good indication of rainfall at dust source areas located upwind. In addition, a wind event may precede a rain

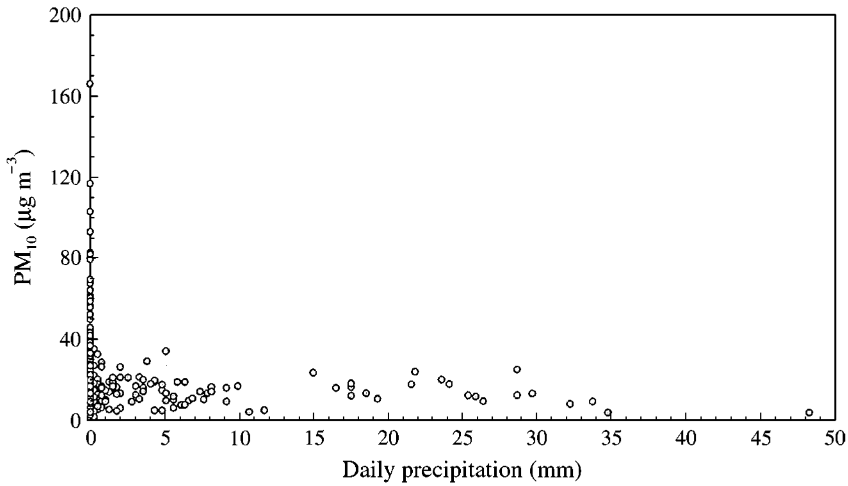

Figure 7. PM_{10} plotted as a function of daily precipitation. Note that there are no daily PM_{10} values greater than 40 $\mu g\, m^{-3}$ for any day with measurable rainfall.

event so that daily rainfall may have little direct correlation with daily dust concentration. On the other hand, rainfall is generally associated with moist atmospheric conditions, and as shown in the previous section, humid conditions can influence ambient dust levels by influencing the moisture content of the uppermost soil surface. Thus, although one may not expect a strong direct correlation between rain and dust, the two may be indirectly correlated through humidity and the effects of humidity on soil moisture. Since rainfall is much easier to measure than humidity and since rainfall data are often more readily available than humidity data, it may be of some interest to at least explore the relationship between rainfall and dust concentration.

Daily rainfall for Lubbock, Texas was obtained from the National Climatic Data Center through a publication called Local Climatological Data (National Climatic Data Center, 1996–1997). The National Weather Service records rainfall at Lubbock International Airport which is located approximately 10 km north-east of the Lubbock Lake dust sampling site. Due to the design of the tipping-bucket rain gage used by the National Weather Service, the smallest amount of rainfall that could be resolved was 0·25 mm (0·01 inches). Trace amounts of rainfall that amounted to less than 0·25 mm were occasionally noted in the precipitation record but in this analysis they were treated as days with no rainfall. PM_{10} concentration is plotted as a function of daily rainfall in Fig. 7. Note that there are no daily PM_{10} values greater than 40 $\mu g\, m^{-3}$ for any day with measurable rainfall.

Surface cover and dust

The region surrounding Lubbock, Texas is significantly impacted by agriculture. According to the 1997 Census of Agriculture, cropland accounts for 76% of the total acreage within Lubbock County and cotton acreage makes up nearly 84% of harvested cropland. Each year, cotton fields in the SHP pass through a regular cycle. Planting begins in May and is completed by mid-June. As cotton plants emerge, they begin to provide minimal ground cover and wind erosion protection. As plants reach the growth stage called first square, the point at which cotton plants begin setting blooms, individual plants have sufficient height and adequate leaf and stem area to provide significant protection of the soil surface. In the SHP, squaring begins in late June and finishes in

Table 4. *Local field conditions as reported by the Texas Agricultural Extension Service and the inferred surface cover fraction*

Date	Fraction squared	Fraction harvested	Surface cover fraction	Date	Fraction squared	Fraction har-vested	Surface cover fraction
6/7/96	0	0	0	11/15/96	1	0·50	0·50
6/14/96	0·04	0	0·04	11/22/96	1	0·55	0·45
6/21/96	0·06	0	0·06	11/29/96	1	0·90	0·10
6/28/96	0·4	0	0·4	12/13/96	1	0·95	0·05
7/5/96	0·65	0	0·65	1/3/97	1	1	0
7/12/96	0·85	0	0·85	6/6/97	0	0	0
7/19/96	0·98	0	0·98	6/13/97	0·02	0	0·02
7/26/96	1	0	1	6/20/97	0·15	0	0·15
10/4/96	1	0	1	6/27/97	0·65	0	0·65
10/11/96	1	0·03	0·97	7/4/97	0·95	0	0·95
10/18/96	1	0·04	0·96	7/11/97	0·95	0	0·95
10/25/96	1	0·08	0·92	7/18/97	1	0	1
11/1/96	1	0·19	0·81	10/3/97	1	0	1
11/8/96	1	0·35	0·65	10/10/97	1	0·01	0·99

mid-July. Between squaring and harvest, most fields have adequate ground cover to protect the soil surface in all but the most extreme wind conditions. Protective vegetative cover is removed during harvest, which takes place from October to December. After harvest, fields lie bare and exposed from January to May.

Information regarding local field conditions was obtained from the Texas Agricultural Extension Service (TAES). A weekly "Crop Report" is prepared by Lubbock County extension agent C. Mark Brown which provides a weekly measure of the fraction of cotton fields that are planted, squaring, and harvested. Due to similarities in regional farming practices and cropping patterns, information obtained from the Lubbock County Crop Report can be extended to a vast region around the sampling site that includes surrounding counties.

Regional cover fraction is defined here as the fraction of fields where plants have reached first square or a growth stage beyond first square minus the fraction of fields that have been harvested. Table 4 contains the fraction squared and fraction harvested as reported by TAES and the estimated surface cover fraction. Linear interpolation was used to estimate daily surface cover from reported weekly values.

PM_{10} is plotted along with surface cover in Fig. 8. The results reveal that most of the large dust events occurred when regional surface cover was at a minimum. As the cotton crop grows to cover and protect the surface in the late summer and early fall (July through October), dust storms become less frequent and the background concentration is reduced significantly.

PM_{10} values are plotted as a direct function of surface cover in Fig. 9. Note that of the 25 PM_{10} values above 40 $\mu g\,m^{-3}$, 21 occurred when the cover fraction was zero. The results also indicate that values above 40 $\mu g\,m^{-3}$ can occur when the surface cover fraction is near unity, especially when winds are extreme and cotton plants are not fully mature.

Conditional dust plots

A somewhat clearer picture of the relationship between wind and dust is obtained when these data are viewed under more restricted conditions. For example, a semi-log plot of

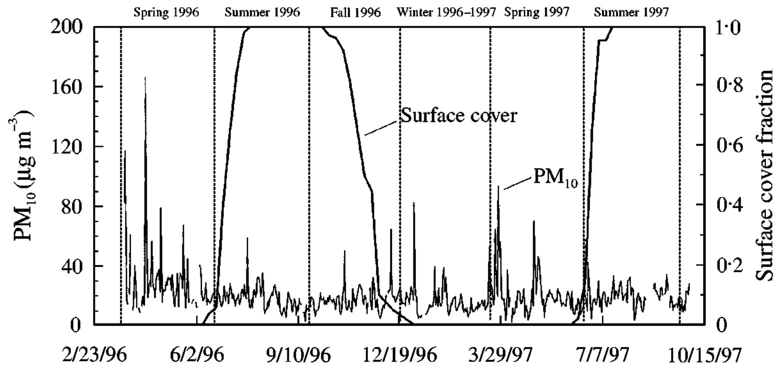

Figure 8. PM_{10} time-series plotted along with surface cover fraction. Note that most dust events are associated with negligible surface cover.

PM_{10} as a function of wind speed for the conditions of bare cotton fields (surface cover = 0) and dry conditions ($RH_{min} < 30\%$) is shown in Fig. 10. Although there is still considerable scatter, one can clearly see two distinct regimes.

For daily wind speeds below about $3\,m\,s^{-1}$, the correlation coefficient between wind speed and PM_{10} concentration is 0·02 indicating that there is little correlation between wind speed and PM_{10} concentration for light winds since few wind gusts exceed the wind erosion threshold and, as a result, few if any fields emit dust. For such light wind conditions, the origin of airborne particulate matter is not related to the wind erosion process and this is reflected in the low correlation between wind speed and PM_{10}.

On the other hand, for daily wind speeds greater than $4\,m\,s^{-1}$ the conditional correlation between wind speed and PM_{10} is much stronger with a correlation coefficient of 0·6. This indicates that for dry and bare conditions, the regional surface is responding to strong wind forces by emitting dust into the atmosphere. In other words, as wind speed increases, more cultivated fields begin to emit dust and those fields already

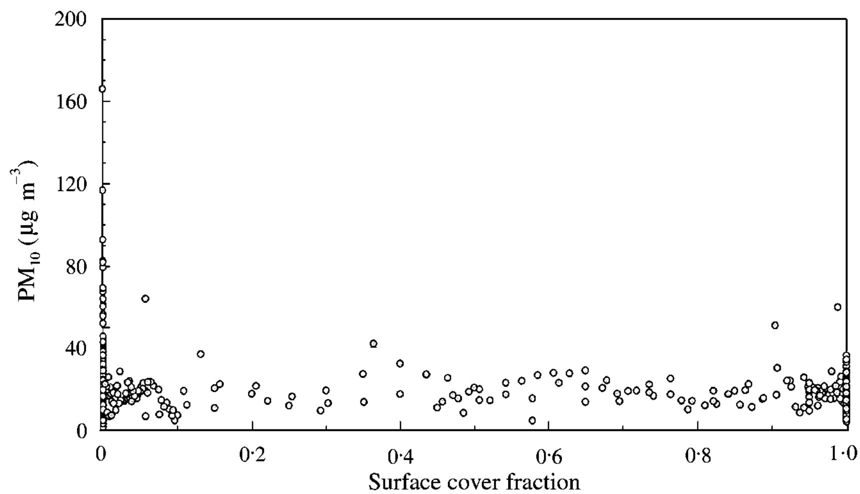

Figure 9. PM_{10} plotted as a function of surface cover fraction.

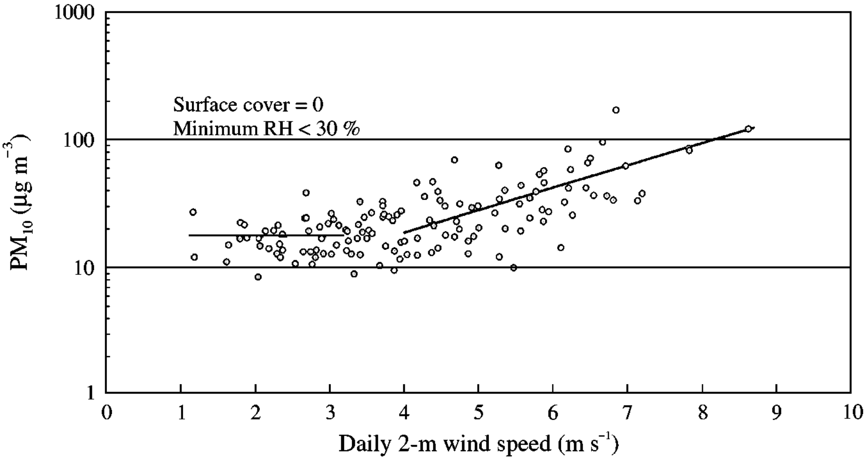

Figure 10. PM_{10} plotted as a function of the daily 2-m wind speed for the conditions of no surface cover and daily minimum relative humidity less than 30%.

emitting dust tend to emit increasing amounts of dust. As a result, dust concentration tends to increase rapidly with wind speed under these conditions.

Conclusions

The arithmetic mean dust concentration for the SHP is low ($\sim 20\ \mu g\, m^{-3}$) indicating a normally clear or dust-free atmospheric condition. This normally low dust condition is intermittently interrupted by dust events that occur most frequently during the spring season. Thus, the Southern High Plains dust record appears to follow a regular annual dust cycle characterized by frequent dust events during spring and few, if any, during the summer and early fall.

The annual dust cycle results from seasonal changes in environmental conditions. Important environmental factors include wind speed, relative humidity, precipitation and surface cover. Most dust events are associated with periods with low humidity ($RH_{min} < 30\%$), no precipitation, negligible surface cover, and daily wind speeds greater than $4\ m\, s^{-1}$.

Wind speed alone is an imperfect indicator of high dust levels in the Southern High Plains since other environmental factors such as surface cover and moisture can significantly reduce regional dust levels, even during high winds. During dry and bare conditions, there are two distinct regimes that are evident. For dry and bare conditions with light winds ($u < 3\ m\, s^{-1}$), wind speed remains below threshold and PM_{10} concentration is independent of wind speed. For dry, bare conditions, and strong winds ($u > 4\ m\, s^{-1}$), PM_{10} concentration exhibits a positive correlation with wind speed.

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